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A quasi-automated generation control strategy for multiple energy storage systems to optimize low-carbon benefits

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Abstract Integrating a battery energy storage system (ESS) with a large wind farm can smooth the intermittent power obtained from the wind farm, but the smoothing function will not be achieved if multiple ESSs are used to smooth the fluctuations in individual wind power plants in a distributed pattern. Therefore, this study focuses on the development of a control strategy to optimize the use of multiple ESSs to accelerate the adoption of wind energy resources. This paper proposes a quasi-automated generation control (QAGC) strategy to coordinate multiple ESSs, which responds to the grid dispatch demand rather than smoothing out the intermittent power from individual wind farms. The aims of QAGC are to ensure that multiple ESSs provide a service that is as balanced as possible, so more wind power systems at various scales can be accepted by the grid, as well maximizing the low-carbon benefits of ESSs. The effectiveness of QAGC is demonstrated by using data from an actual gigawatt scale cluster of wind plants.

Keywords Control strategy, Low-carbon benefits, Multiple battery energy storage systems, Quasi-automated generation control

1 Introduction

Increasing the ratio of renewable energy in terminal consumption is an effective way of achieving a low-carbon energy supply. In China, the ratio of renewable energy in end use will reach 20% by 2020 [1] according to the National Plan for Medium and Long Term Renewable Energy Development. Therefore, the energy structure, low-carbon benefits, energy conservation, and emission reduction problems are receiving increasing attention [2, 3].

Several incentive policies for promoting wind energy have been issued in China. In 2007, the National Development and Reform Commission, the Environmental Protection Administration, and the Energy Office jointly formulated the "Energy Generation Scheduling Approach (Trial Implementation)" [4], in which the wind power was highlighted as having the main scheduling priority.

However, the wind power is intermittent and the uncertainty of the wind power can have many adverse effects on the economical operation of power systems, possibly endanger the safe operation of power systems [5, 6]. Thus, the scales of wind power systems integrated into the grid are restricted at present, and addressing the uncertainty of the wind power and its integration remains a problem.

The development of wind power prediction systems is a valid approach for dealing with the wind power uncertainty. The National Energy Bureau has asked operators to improve the wind power prediction accuracy and to enhance the management of wind power sources. However, the wind power forecasting accuracy is affected by many factors at present and it is still difficult to satisfy the secure and economic operation requirements of power systems.

Energy storage systems (ESSs) can transform energy usage in terms of time and space, and they are regarded as an important way of improving the characteristics of wind power sources [7, 8]. Demonstration projects such as the Hebei Zhangbei wind storage demonstration project and Liaoning Woniushi wind storage demonstration project have improved the wind power output characteristics, as

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well as providing valuable experience in terms of running large-scale ESS applications [9, 10].

In fact, the integration of wind power can have adverse effects on power systems, which are caused by volatility in the overall wind power network, rather than the power output volatility of local or single wind farms. This is because that a power system is a large inertial system with a strong anti-interference capacity. However, if the wind power fluctuations exceed the adjustment capacity of the system, the wind power must be stabilized and regulated, but the ESS control strategies used to smooth wind power fluctuations on single wind farms might lead to the excessive regulation.

Given recent breakthroughs and the lower prices of large-scale energy storage technology, it has broader application prospects. Indeed, a power system auxiliary service market based on large-scale ESSs is developing. Multiple ESSs must address the task of managing control functions and increasing the different scales of wind power systems that can be integrated into the grid.

Previously, researchers have focused on the operational control technology for single type ESSs [11–13] and the control performance optimization for hybrid ESSs [14–16], improving the storage system optimization configuration to enhance the performance of wind power access systems [17–20]. Thus, many studies have investigated large-scale ESSs, but the problem of coordinating control for multiple ESSs has not been addressed previously.

The integration of large-scale wind power systems requires support from the flexible power system auxiliary service market. In the present study, a control strategy based on a power system auxiliary service for large-scale ESSs is described, in which the offset effect that occurs with multiple ESSs is demonstrated when smoothing wind power fluctuations in a distributed pattern. A quasi-automated generation control (QAGC) strategy is proposed for multiple ESSs, which satisfies the power system control requirements for electric power and relaxes the bottleneck to accommodate the wind power in the grid. This approach regulates the performance of ESSs, broadens the scale of wind power systems accepted by the grid, and optimizes the low-carbon benefits of ESSs.

2 Offset effect in wind power storage systems with distributed control

Due to space–time differences in the energy distribution, the wind power outputs vary among wind farms. In contrast to smoothing the total deviation in the power of a cluster of wind farms, smoothing the wind power fluctuations of multiple ESSs based on the distributed control leads to energy offsets due to charging and discharging by the ESSs, which is referred to as the "offset effect".

The offset effect is shown in Fig. 1 based on smoothing the power output fluctuations of two wind farms using ESSs. For a cluster of two wind farms, the clustering output power is $P_{\Sigma\mathrm{wind}}$, the total reference power is $P_{\Sigma\mathrm{ref}}$, and the deviation is ΔP_{Σ}. With the distributed control, the corresponding individual power outputs are $P_{\mathrm{wind.1}}$ and $P_{\mathrm{wind.2}}$, the individual reference powers are $P_{\mathrm{ref.1}}$ and $P_{\mathrm{ref.2}}$, and the individual deviations are ΔP_1 and ΔP_2.

As shown in Fig. 1, wind storage system No. 1 needs to use its power to charge an ESS in order to store surplus wind power, whereas wind storage system No. 2 needs to discharge the power to compensate for the lack of the wind power, the equations are shown as follows:

$$P_{\mathrm{BESS.1}} = P_{\mathrm{wind.1}} - P_{\mathrm{ref.1}} \tag{1}$$

$$P_{\mathrm{BESS.2}} = -(P_{\mathrm{wind.2}} - P_{\mathrm{ref.2}}) \tag{2}$$

where $P_{\mathrm{BESS}.i}$ is the ESS charging power for part i $(i = 1,2,\ldots,n)$.

After smoothing the differences in power between the two wind farms in the cluster, the charge power of the ESS is

$$P_{\Sigma\mathrm{BESS}} = P_{\mathrm{wind.1}} - P_{\mathrm{ref.1}} + P_{\mathrm{wind.2}} - P_{\mathrm{ref.2}} \tag{3}$$

and the following equation is always true.

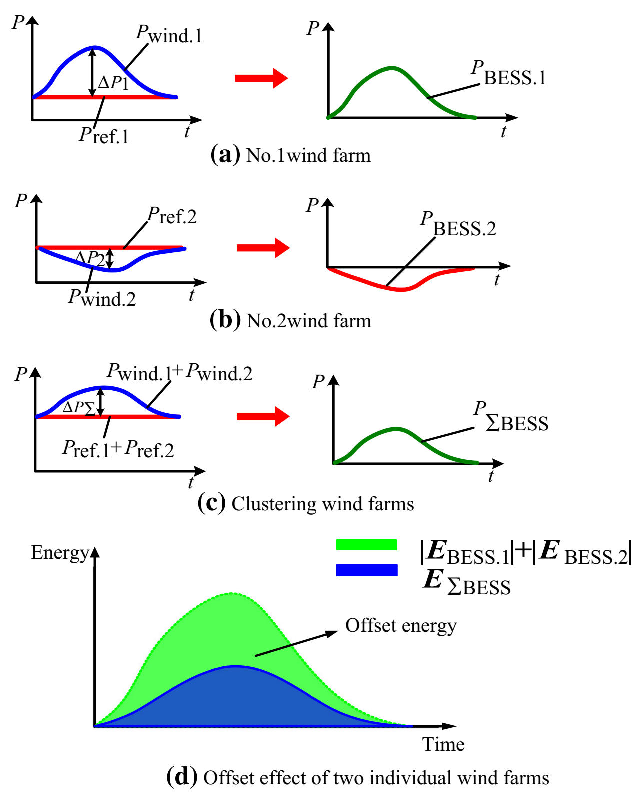


Fig. 1 Schematic diagram of offset effect when smoothing outputs of two individual wind farms

$$|P_{\Sigma \mathrm{BESS}}| \le |P_{\mathrm{wind.1}} - P_{\mathrm{ref.1}}| + |P_{\mathrm{wind.2}} - P_{\mathrm{ref.2}}| \tag{4}$$

In the same manner, when clustering wind storage systems that comprise n wind farms with ESSs, the following is always true.

$$|P_{\Sigma \mathrm{BESS}}| \le \sum_{i=1}^{n} |P_{\mathrm{BESS}.i}| \tag{5}$$

Thus, compared with smoothing the total power deviation, the ESS control cost is greater when smoothing the deviations in the power output from individual wind farms.

We propose the concepts of offset energy and an offset energy factor to measure the degree of ESS energy offset during the distributed control, which are shown as follows:

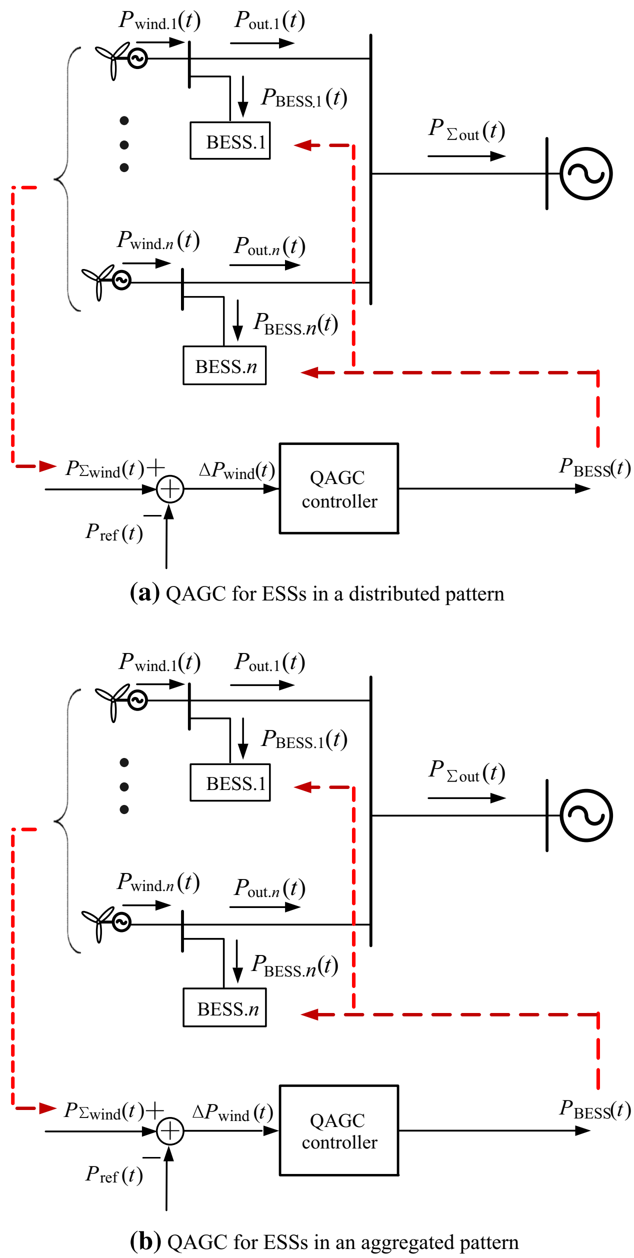
$$E_{\mathrm{offset}} = \sum_{i=1}^{n} \left[\int |(P_{\mathrm{wind}.i} - P_{\mathrm{ref}.i})| \mathrm{d}t \right] - \int |P_{\Sigma \mathrm{wind}} - P_{\mathrm{ref}}| \mathrm{d}t \tag{6}$$

$$k = \frac{E_{\mathrm{offset}}}{E_{\Sigma \mathrm{BESS}}} = \frac{E_{\mathrm{offset}}}{\sum_{i=1}^{n} \left[\int |(P_{\mathrm{wind}.i} - P_{\mathrm{ref}.i})| \mathrm{d}t \right]} \tag{7}$$

where $P_{\Sigma \mathrm{wind}}$ and P_{ref} are the total wind output power and total wind reference power, respectively. If the offset energy E_{offset} is higher, the stated offset energy when charging and discharging among ESSs is greater with the distributed control. The offset effect factor k reflects the ratio of the offset energy in the total charge and discharge energy with the distributed control.

3 A QAGC strategy for a large-scale ESS

The adverse effects of the wind power integration into a grid are attributable to the wind power uncertainty of the whole network rather than fluctuations in the output power of single wind farms or local wind farms. In order to improve the networking performance of wind farm groups, it is only necessary to regulate the overall wind power of the network to ensure that it does not deviate from the allowable value. Using the fluctuating component of the system payload (the wind power is treated as a negative load) as a regulatory criterion to determine the allowable wind power value for the whole network can fully exploit the wind power potential accepted by the grid, and effectively improve the safety of the wind power integration into the grid. The proposed QAGC strategy allows multiple ESSs to satisfy the power system control requirements and it relaxes the bottleneck to accommodate the wind power produced at various scales in the grid.

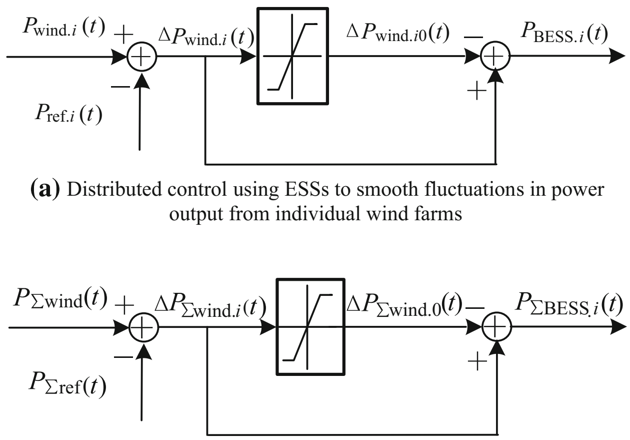


(a) QAGC for ESSs in a distributed pattern

(b) QAGC for ESSs in an aggregated pattern

Fig. 2 QAGC strategies for ESSs in response to grid dispatch commands

Due to recent breakthroughs in the large-scale energy storage technology and lower prices, a power system auxiliary service market based on large-scale ESSs is developed. Irrespective of whether ESSs are installed in the vicinity of wind farms in a distributed pattern at the beginning of the application or installed in an aggregated pattern, both approaches can facilitate regulatory participation in a power system auxiliary service market, where control strategies will assist service regulation for the overall power system. Figures 2 and 3 show examples of ESS installation patterns and control strategies.



(a) Distributed control using ESSs to smooth fluctuations in power output from individual wind farms

(b) Aggregated control using ESSs to smooth fluctuations in power output from a cluster of wind farms

Fig. 3 Use of ESSs in distributed and aggregated control patterns

For multiple storage systems with a distributed pattern, as shown in Fig. 2a, we assume that the state of charge for each ESS unit is the same, and thus by assessing the total charging power according to the proportion of the overall capacity, the ESS charging power using the QAGC strategy is:

$$\begin{cases} P_{\mathrm{BESS}}(t) = \begin{cases} P_{\Sigma\mathrm{wind}}(t) - P_{\mathrm{ref}}(t) & P_{\Sigma\mathrm{wind}}(t) > P_{\mathrm{ref}}(t) \\ 0 & P_{\Sigma\mathrm{wind}}(t) \le P_{\mathrm{ref}}(t) \end{cases} \\ P_{\mathrm{BESS}.i}(t) = \dfrac{P_{\mathrm{BR}.i}}{\sum P_{\mathrm{BR}.i}} P_{\mathrm{BESS}}(t) \\ E_{\mathrm{BESS}.i}(t) = E_{\mathrm{BESS}.i}(t-\Delta t) + P_{\mathrm{BESS}.i}(t)\Delta t\eta \end{cases} \tag{8}$$

where the constraint conditions are:

$$\begin{cases} 0 \le P_{\mathrm{BESS}.i}(t) \le P_{\mathrm{BR}.i} \\ 0 \le E_{\mathrm{BESS}.i}(t) \le E_{\mathrm{ER}.i} \end{cases}$$

P_{BESS} is the total ESS charging power; $P_{\mathrm{BR}.i}$ and $E_{\mathrm{BR}.i}$ are the rated power and the rated energy capacity for part i ($i = 1,2,\ldots,n$), respectively.

When the overall wind power of the network exceeds the allowable value for the whole network, the ESSs are controlled to absorb the surplus wind power.

When the state of charge (SOC) of ESSs reaches to the maximum value (e.g. 1.0), the ESSs are controlled during the higher load period to discharge for possessing the maximum upward reserve capacity.

With multiple ESSs in an aggregated pattern, as shown in Fig. 2b, the control is achieved more directly without any requirements for coordinating communication.

Figure 3 compares the usage of an ESS to smooth the power output from a wind farm in a distributed control pattern and the power output from a wind farm cluster in an aggregated control pattern. In Fig. 3, the reference input $P_{\mathrm{ref}.i} = P_{\mathrm{forecast}.i}$ corresponds to the distributed control to smooth the wind power according to the predicted power deviation, and the reference input $P_{\Sigma\mathrm{ref}} = P_{\Sigma\mathrm{forecast}}$ corresponds to the aggregated control to smooth the overall wind power of a cluster of wind farms based on the predicted power deviation.

The corresponding control parameters for the three ESS control patterns are shown in Table 1. In the table, $P_{\mathrm{windspace}}$ is the wind power accommodation capacity of the power grid.

As shown in Fig. 3 and Table 1, when $P_{\mathrm{ref}.i} = P_{\mathrm{forecast}.i}$, and by using ESSs to smooth the predicted wind power error $\Delta P_{\mathrm{wind}.i}$ for an individual wind farm in a distributed pattern, the controlled variable is $P_{\mathrm{BESS}.i}$ and the wind output power is $P_{\mathrm{out}.i}$ after smoothing. This control pattern improves the certainty of the power output from an individual wind farm, but the effective regulation of the ESSs is reduced severely due to the offset effect.

When $P_{\Sigma\mathrm{ref}} = P_{\Sigma\mathrm{forecast}}$, the control strategy described above can improve the certainty of the power output from the wind farm cluster. Storage systems are used to improve the source characteristics of wind farms. The available wind power capacity of the grid is not considered at this time, thus ESSs may still be over-regulated, which reduces the effectiveness of the regulation. The contribution of ESSs to increasing the system capacity when handling the uncertainty of power regulation is also ignored.

When $P_{\mathrm{ref}} = P_{\mathrm{windspace}}$, the potential wind power accepted by systems can be fully exploited. Most of the time, the ESSs do not need to be activated and the ESSs are only required to charge to absorb the excess wind energy when the wind power exceeds the accommodation ability of the power grid. Thus, the ESSs are equivalent to "spinning" reserve for the system. If the capacity configuration reaches a sufficient level, it can greatly improve the ability of the system to handle uncertain power fluctuations.

Table 1 Comparison of three control strategies

Control pattern	P_{ref}	Control variable	Control object	Output
Distributed control	$P_{\mathrm{forecast}.i}$	$P_{\mathrm{BESS}.i}$	$P_{\mathrm{wind}.i}$	$P_{\mathrm{out}.i}$
Aggregated control	$P_{\Sigma\mathrm{forecast}}$	$P_{\Sigma\mathrm{BESS}.i}$	$\sum P_{\mathrm{wind}.i}$	$\sum P_{\mathrm{out}.i}$
Quasi-AGC control	$P_{\mathrm{windspace}}$	$P_{\Sigma\mathrm{BESS}.i}/P_{\mathrm{BESS}}$	$\sum P_{\mathrm{wind}.i}$	$\sum P_{\mathrm{out}.i}$

4 Simulation example

In this example, a gigawatt (GW)-scale cluster of wind farms with a storage system is considered. The distributed control is compared to smooth fluctuations in the power output of individual plants and aggregated control to smooth the power output of clustering wind farms by using QAGC to adapt to the needs of the power system control. To facilitate the large-scale integration of wind power in the grid, an important reference is provided for configuring the capacity of multiple ESSs and control target selection.

The GW-scale cluster of wind storage systems is shown in Fig. 4, which comprises wind farms and their support ESSs (charge/discharge efficiency is 83%, initial state of charge is 0.5), while the installed capacities of the wind storage systems are shown in Table 2. The capacity of the wind farm cluster storage system is 59.66–1193 MW, or 119.30 MW/h.

The data length is 24 h and the sampling interval is 5 min ($24 \times 12 = 288$) in this example. The curves used to predict the wind generation by eight wind farms and the actual power curves are shown in Appendix 1, and assume that the maximum allowable prediction error ΔP is ± 0.05 p.u.

For comparison conveniently, the given grid-connected wind power space is greater than the actual wind power of the wind farm group, as shown in Fig. 5.

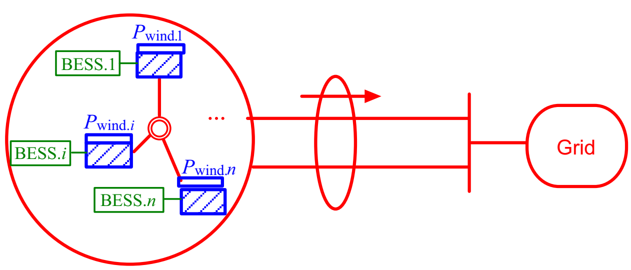


Fig. 4 Multiple wind-storage systems integrated into grid

Table 2 Installed capacity of the wind-storage systems

No.	Installed wind capacity (MW)	Installed of ESS	
		Rated power (MW)	Energy capacity (MWh)
1	349	17.45	34.90
2	349	17.45	34.90
3	99	4.95	9.90
4	99	4.95	9.90
5	99	4.95	9.90
6	99	4.95	9.90
7	49.5	2.48	4.95
8	49.5	2.48	4.95
Total	1193	59.66	119.30

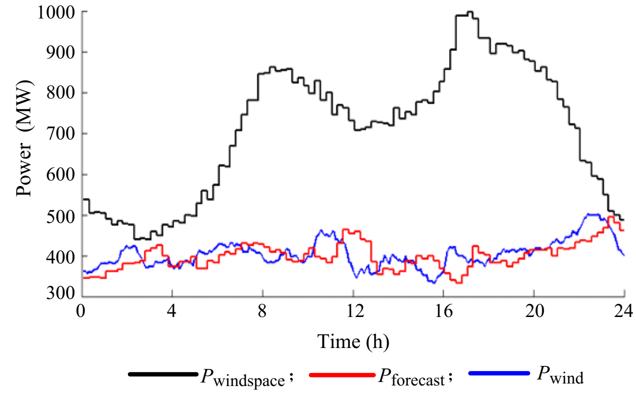


Fig. 5 Curves for grid connected to wind power space, wind power and predicted power for wind farm cluster

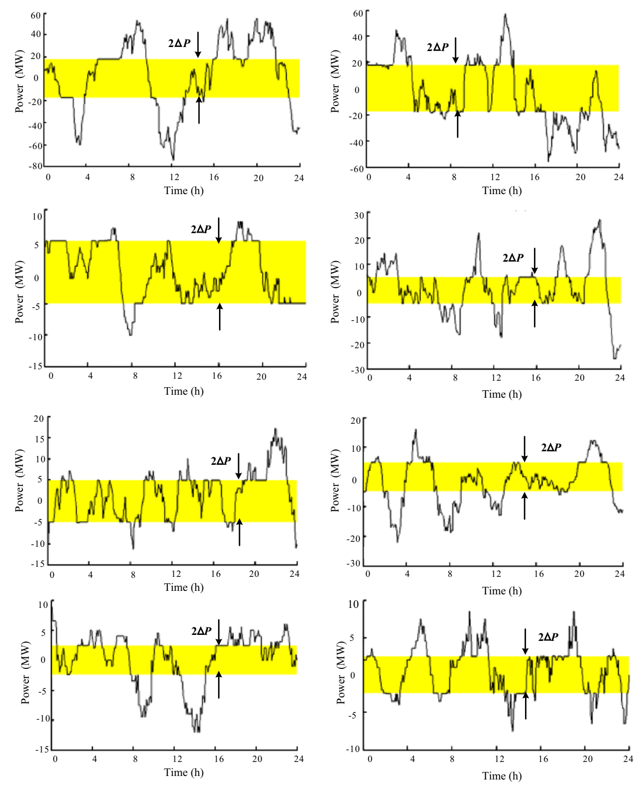


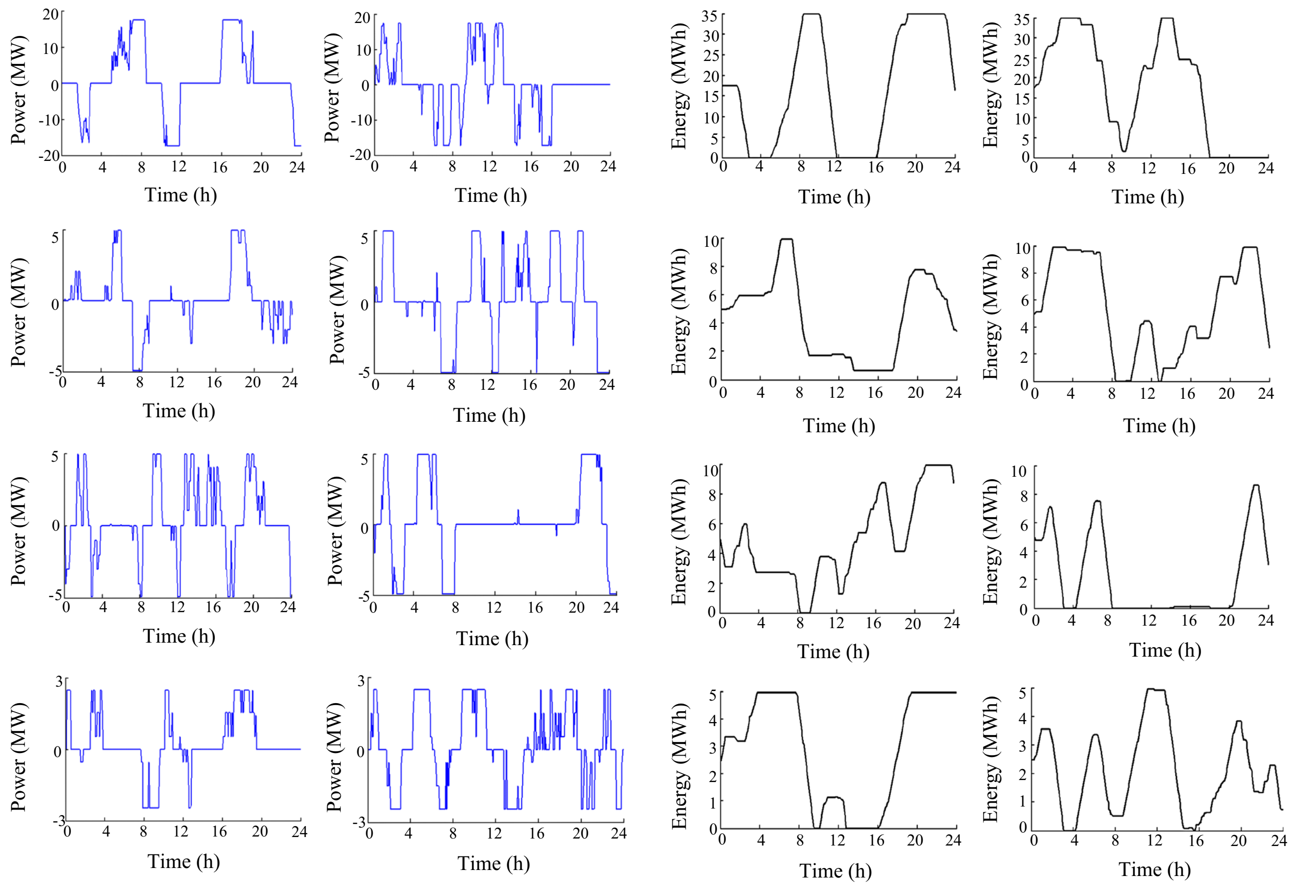
Fig. 6 Curves of distributed smoothed predicted error of wind power for each wind plant

When employing QAGC strategy, ESSs are controlled to discharge during the higher load period, e.g. about 6 a.m.–9 a.m. in this case study.

4.1 ESSs regulation effects of three different control strategies

1) Distributed control using power error of single wind plants as reference input

Figure 6 shows the curves of the distributed smoothed predicted error of wind power for each wind plant. Figure 7



(a) Curves of charge-discharge power for each ESS with distributed control strategy

(b) Curves of energy for each ESS with distributed control strategy

Fig. 7 Curves of charge–discharge power and energy for each ESS with distributed control strategy

shows the curves for the charge–discharge power and energy for each ESS with the distributed control strategy.

As shown in Fig. 6, the generation power characteristics of the wind plants are different. For a given storage capacity and allowable prediction error, the integrated wind power cannot be constrained within the range of the allowable error with the distributed control strategy.

As shown in Fig. 7, each ESS is regulated frequently (action frequency is 127/24 rates/h, accumulative throughput capacity is 425.50 MW/h); thus, the energy "offset effect" between charging and discharging among multiple ESSs occurs during some periods.

2) Integrated control using power error of a wind farm group as reference input

Figure 8 shows the curves of the smoothed predicted error of power output for a wind farm group. Figure 9 shows the curves for the charge–discharge power and energy for the total ESSs with an aggregated control strategy.

As shown in Figs. 8 and 9, the total power integrated from the wind farm group exceeds the allowable error range only for a small period of time. Thus, the ESS control frequency is decreased greatly and the effect of control is obviously improved (action frequency is 7/24 rates/h and accumulative throughput capacity is 43.17 MW/h).

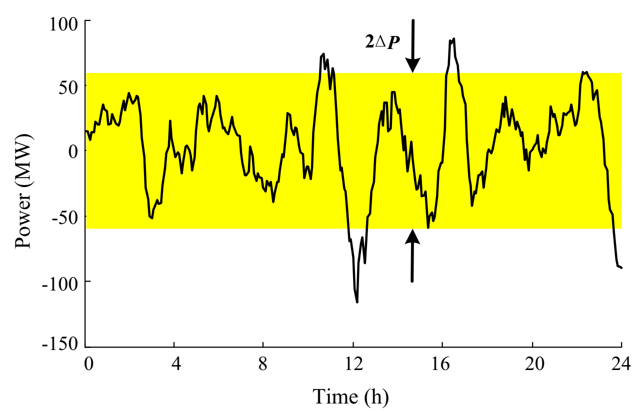


Fig. 8 Curves of the predicted error power for a cluster of wind farms

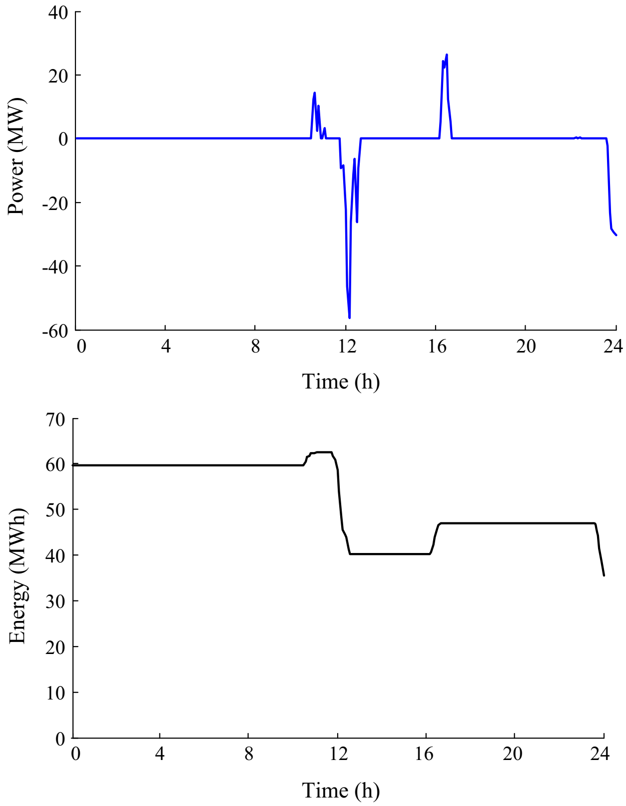


Fig. 9 Curves of charge–discharge power and energy for total ESSs with aggregated control strategy

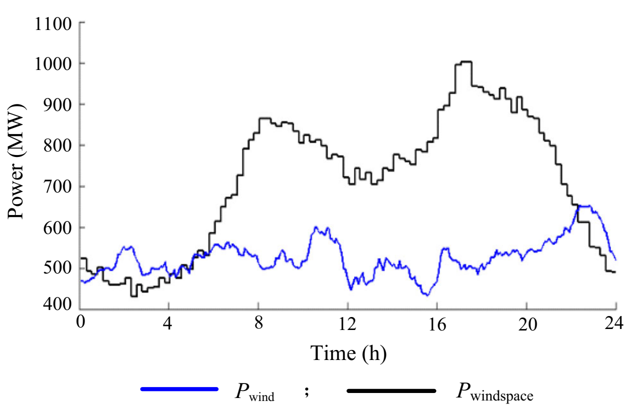


Fig. 10 Curves of consequent wind power and grid-connected wind power space with 1.3 times installed capacity (1551 MW)

3) QAGC using grid-connected wind power space as reference input

As shown in Fig. 5, the ESSs do not need to be regulated since the actual wind power output is within the grid-connected wind power space and the wind power can be integrated into the grid completely.

Giving the wind power output is proportional to the installed capacity and enlarging the installed wind capacity to 1.3 times (1551 MW) of that shown in Table 2, the consequent wind power output shown in Fig. 10 occasionally exceeds the grid-connected wind power space and the ESSs need to be charged. As a result, the scale of the grid-connected wind power can be increased. The corresponding curves for the charge–discharge power and the energy change in the ESSs are shown in Figs. 11 and 12, respectively.

The maximum charging power of the ESSs is 59.55 MW and the control frequency is reduced greatly using the QAGC strategy, as shown in Figs. 11 and 12. The cumulative throughput capacity is 92.46 MW/h with more than 2869.3 (MWh)/day wind energy accepted, and the effect of regulation is obviously improved.

4.2 Comparison of ESS smoothing using three control strategies

If the excess wind power is viewed as curtailed wind power, the control effects of different ESS control strategies can be evaluated using three indices: the curtailed wind energy, the energy throughput, and the reduced equivalent CO_2 emissions. Table 3 shows

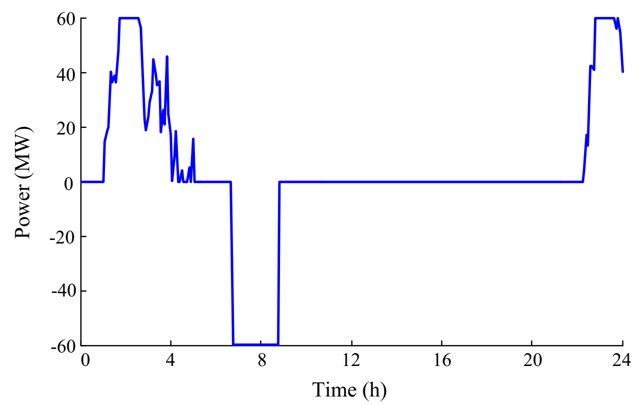


Fig. 11 Charge power curves for ESSs using QAGC strategy

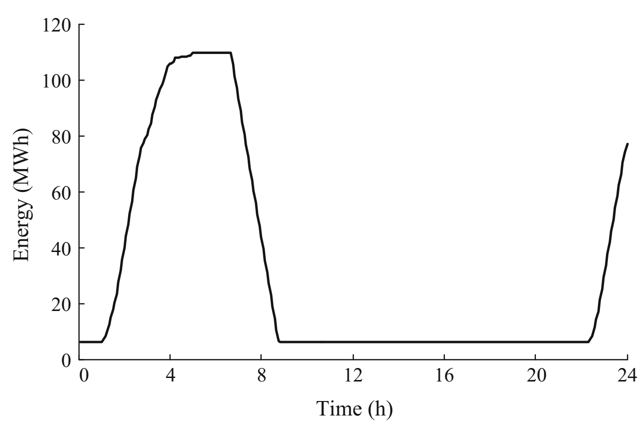


Fig. 12 Change in energy curves of ESSs using QAGC strategy

Table 3 ESS performance comparison using three control patterns

Control pattern	Curtailed wind power (MWh)	Throughput capacity (MWh)	CO_2 emission (kg)
Distributed control	1066.34	425.50	1041814
Aggregated control	113.71	43.17	111095
Quasi-AGC control	−2869.3	92.46	−2803306

Note: negative curtailed wind power values represent more connected wind power, and negative CO_2 values represent reduced emissions

the evaluation results for these different control strategies.

As shown in Table 3, based on the same storage configuration, the curtailed wind energy and energy throughput of the ESSs are reduced by 952.63 and 382.33 MW/h, respectively, using the aggregated control strategy compared with the distributed control strategy. Theoretically, 1 kW/h of electricity is equivalent to 0.977 kg CO_2 emissions, thus the CO_2 emissions would be reduced by 930719 kg. The grid-connected wind energy increment and the corresponding reduction in the CO_2 emissions are 2983.01 MW/h and 2914400 kg, respectively, using the QAGC strategy compared with the aggregated control strategy. Clearly, the low-carbon benefits of ESSs are optimized by the QAGC strategy.

5 Conclusion

Based on an analysis of the wind storage system control problem, "offset effect" is identified among multiple ESSs when smoothing wind power fluctuations using a distributed pattern. Thus, the QAGC strategy is proposed for multiple ESSs to address the need for power system control. A GW-scale wind storage cluster system is used as an example. In contrast to distributed control, the "offset effect" is handled with multiple ESSs and the curtailed wind power caused by wind power fluctuations is avoided by using the QAGC strategy. Thus, the regulatory burden on the storage system is reduced, while the CO_2 emissions are also reduced by 2914400 kg. The proposed method enhances the regulatory efficiency and improves the low-carbon benefits of ESSs.

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Appendix 1

See Figs. 13 and 14.

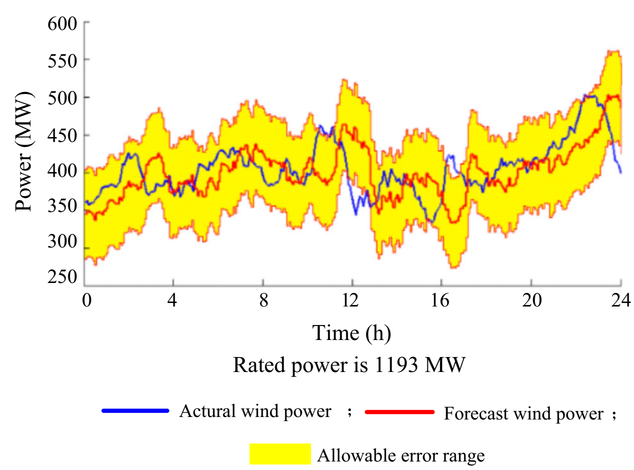
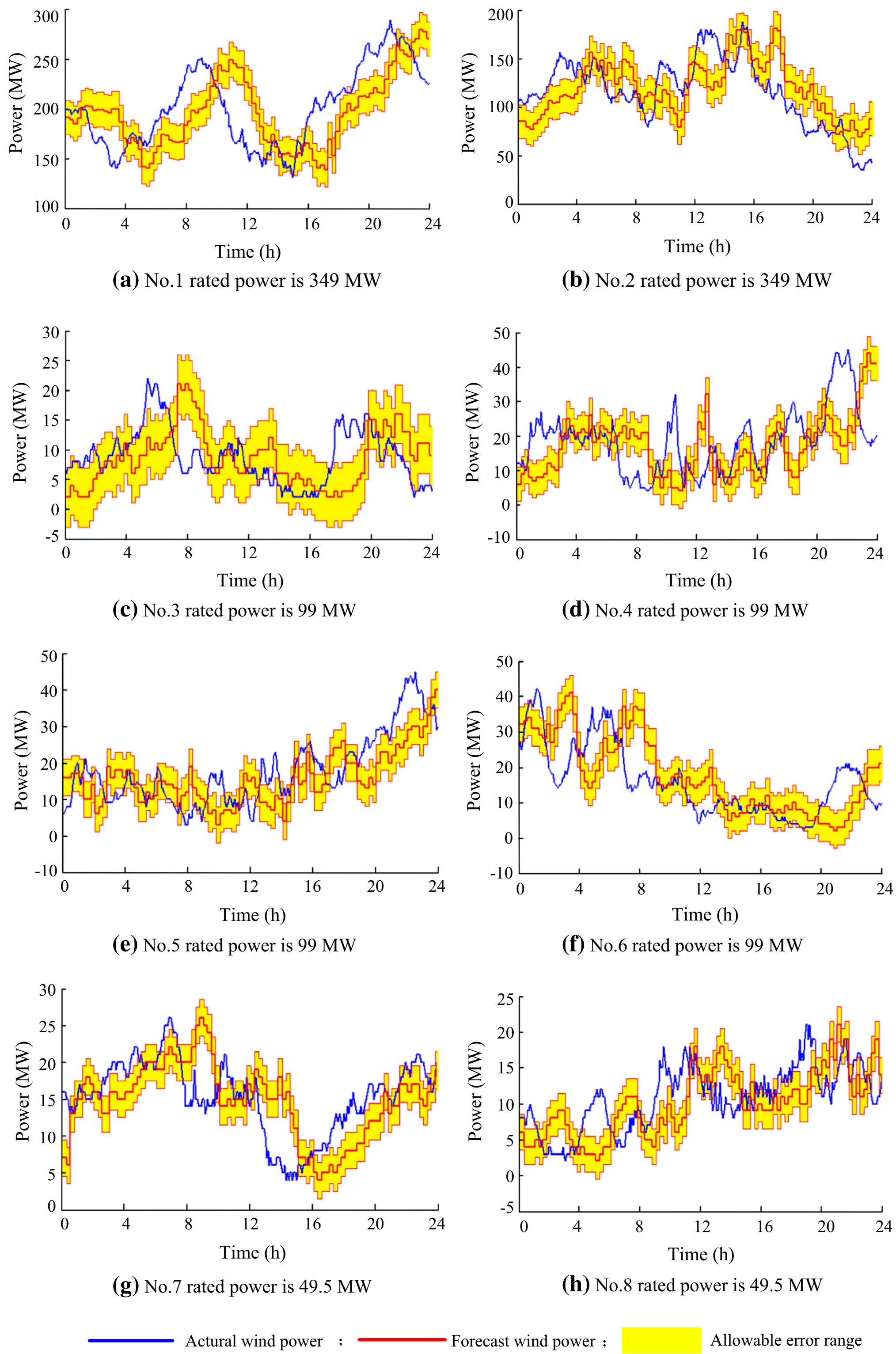


Fig. 13 Cluster of wind plants: actual power, predicted power, and accepted predicted error range



(a) No.1 rated power is 349 MW

(b) No.2 rated power is 349 MW

(c) No.3 rated power is 99 MW

(d) No.4 rated power is 99 MW

(e) No.5 rated power is 99 MW

(f) No.6 rated power is 99 MW

(g) No.7 rated power is 49.5 MW

(h) No.8 rated power is 49.5 MW

Fig. 14 Eight wind plants: actual power, predicted power and accepted predicted error range

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